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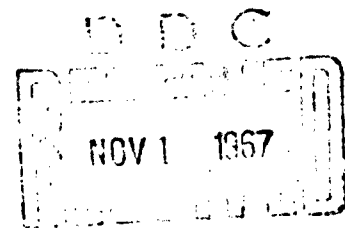
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INVESTIGATION OF ELECTRONIC INTERACTION WITH OPTICAL RESONATORS FOR MICROWAVE GENERATION AND AMPLIFICATION

REPORT NO. 9

By
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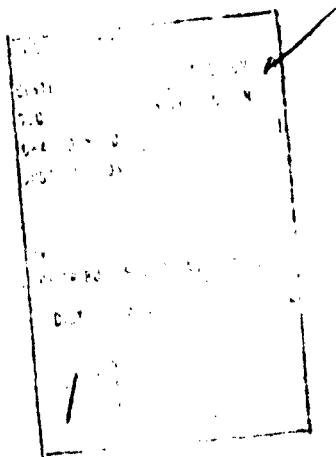
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INVESTIGATION OF ELECTRONIC INTERACTION
WITH OPTICAL RESONATORS FOR MICROWAVE
GENERATION AND AMPLIFICATION

Report No. 9

16 March 1967 - 15 July 1967

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Fort Monmouth, New Jersey, 07703

by: H. Jory

OBJECTIVE

The object of this program is to study electronic interactions using resonators that are large compared to a wavelength thereby avoiding the fabrication and power density difficulties of conventional resonators at millimeter and submillimeter wavelengths.

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ABSTRACT

Design changes in the improved version (model 2) of the monotron oscillator are discussed. Cold test work is described which has led to what appears to be a good solution to the problem of orienting the resonances in the oscillator cavity for good coupling to the output waveguide.

Construction and initial experimental results with model 2 are described. Oscillation has been observed in resonances ranging from $TE_{6,1,1}$ at 48.8 GHz through $TE_{9,1,1}$ at 69.5 GHz.

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I. PURPOSE

The purpose of this contract is the investigation of interactions between electron beams and resonant structures which are large compared to a wavelength. Such structures avoid the power density and fabrication difficulties normally encountered at millimeter and submillimeter wavelengths. The investigation is to include both analysis and experimental demonstration of devices operating at millimeter or submillimeter wavelengths.

II. FACTUAL DATA

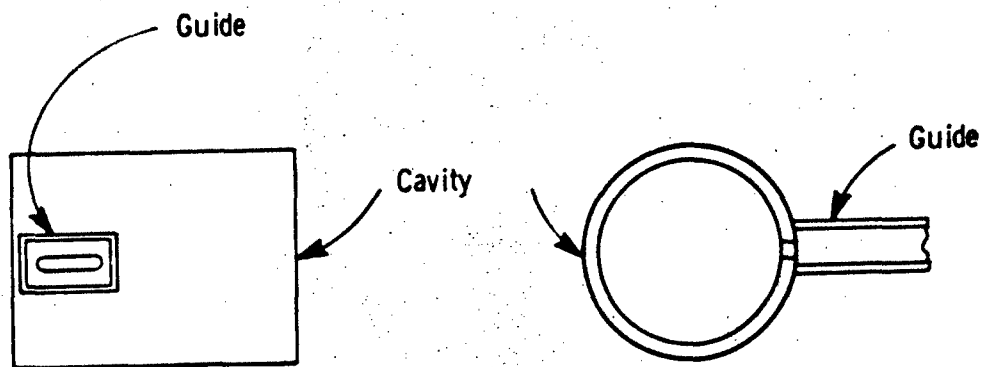
A. REDESIGN OF THE EXPERIMENT

The redesign of the second experimental oscillator was completed during this period. Considerable study was given to methods of mode orientation in the oscillator cavity for improved coupling to the output waveguide. Basically the problem arises because the oscillator cavity has complete angular symmetry. For each cavity resonant mode there exists another orthogonal mode which has the same number of radial, angular, and axial variations, and the same resonant frequency, but a different angular orientation. One of the degenerate modes will have a maximum E_r field at the angular position where the other mode has a maximum H_z field.

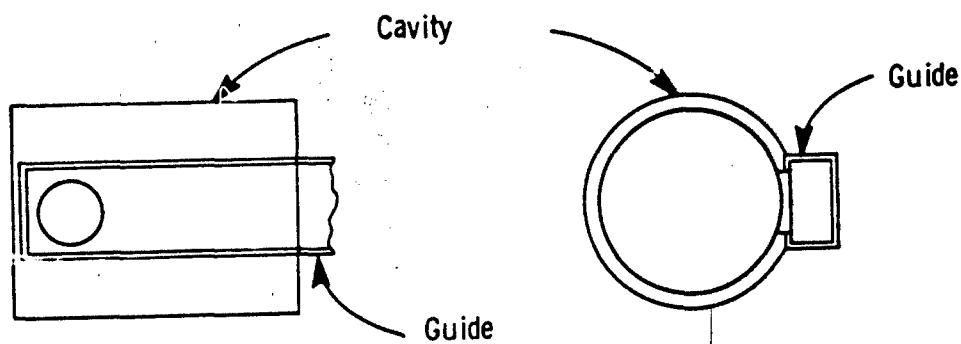
If the output waveguide has a single coupling hole which couples, for example, only to H_z , then the mode with H_z at that position will be coupled to the output guide, but the E_r mode will not. Since the E_r mode is more lightly loaded, the beam will excite this mode and negligible power will be coupled out. To avoid this situation, the undesired mode must either be detuned in frequency or resistively loaded more heavily than the desired mode.

Cold test methods were used to study several approaches for mode control. Frequency detuning was tried by the introduction of a radial metal fin which shorted out the E_r field at one angular position for the entire length of the cavity. The measurements indicated that the mode with E_r at that position was lowered in frequency by about 1%, and the Q of the resonance was lowered by about 50%. The other mode, with H_z at the position of the fin, was not altered. Neither the 1% frequency change nor the 50% Q change is considered adequate for good mode control.

Resistive loading of the undesired mode was tested by building a cold test structure with two coupling guides at the same angular position. The two coupling techniques are pictured schematically in Figures 1 (a) and 1 (b). For H coupling, a long slot was used with its long dimension parallel to the H_z field in the cavity and the



(a) Slot for Coupling Waveguide
H Field to H_z Field in Cavity



(b) Hole for Coupling Waveguide
to E_r Field in Cavity

Figure 1.

H field in the guide. For the E coupling, a large hole is required to get the appreciable coupling. The axis of the hole is parallel to the E_r field in the cavity and the E field in the guide. For the E coupling, the axis of the waveguide can be either parallel to the cavity axis as shown or tangential to the cylindrical wall of the cavity. The axial orientation is preferred in this case because it allows angular symmetry of the guide with respect to the coupling hole in the cavity.

In the E coupling arrangement, a short was placed at the end of the guide near the coupling hole. The position of the short was adjusted for optimum characteristics of the coupler (i.e., for strong coupling with minimum frequency variation). To obtain critical coupling or overcoupled conditions with the E coupler it was necessary to make the hole diameter nearly the full width of the guide. The optimum position of the short was at the edge of the hole. It was found that the coupling could be increased considerably by using reduced-height guide near the coupling hole.

For the H coupling system, it was necessary to make the slot the full width of the guide in order to realize an overcoupled condition. The small dimension of the slot does not influence the coupling much.

The original idea in testing with both E_r - and H_z -coupled guides was to choose coupling hole sizes so that the E_r coupling was somewhat larger than the H_z coupling. Then the oscillator would operate with the H_z orientation, and the useful output would be taken out through the H_z coupler. The E_r coupler would merely be connected to a dummy load. In the course of the measurements it was observed that when large E_r coupling holes were introduced, the Q's of the H_z -oriented resonances were noticeably decreased. Subsequent investigation indicated that the decrease in Q was caused by the E_r coupling hole acting as a perturbing element which coupled energy from an H_z -oriented resonance to other cavity modes which radiate through the drift tube holes in the ends of the cavity. The decrease in Q of an H_z resonance does not depend on the type of termination on the E_r coupling guide, but only on the geometry immediately surrounding the E_r coupling hole.

The cold test observations suggested that the simplest approach to mode control would be to make use of the perturbation effect of the E_r coupling hole. To do this it is necessary only to make the E_r coupling hole large enough to achieve a somewhat overcoupled condition for the resonance with E_r at the position of the coupling hole. When this is done, the resonance with H_z at the same position will be sufficiently lowered in Q by scattering of energy into other modes that the oscillator should operate in the desired E_r mode. In the cold tests it was found that the H_z modes could be perturbed to the point where resonances could no longer be observed by reflection techniques.

The cold test measurements were performed at X-band using WR 112 guide. All dimensions were scaled up in size by a factor 7.58 compared with the desired millimeter wave structure. The factor 7.58 is the ratio of the major dimensions of the WR 112 and WR 15 guides. Representative cold test results are given in Table I for resonances from $TE_{6,1,1}$ to $TE_{12,1,1}$. The reflected power column is an indication of the degree of coupling realized through an E_r coupling hole 0.812 inch in diameter, with a wall thickness of 0.070 inch using half-height (1.122 inches x 0.250 inch) waveguide. The $TE_{6,1,1}$ through $TE_{9,1,1}$ resonances are undercoupled. Others are critically coupled or overcoupled as indicated. With this size of E_r coupling hole, H_z resonances were no longer observable through a long-slot H_z coupler. The next to last column in the table gives the expected millimeter wave resonant frequency, and the final column gives the expected value of synchronous angular velocity.

Because the axial length of the millimeter wave resonator is large compared with a wavelength, resonances having more than one axial variation were observed. For example, resonances with up to five axial variations were observed with ten azimuthal variations ($TE_{10,1,1}$ through $TE_{10,1,5}$). The modes with more than one axial variation have higher resonant frequencies. The limitation on the number of axial variations occurs when the frequency becomes high enough that the drift tube is no longer cut off. For example, the $TE_{10,1,6}$ resonance is not observed because the drift tube propagates at its resonant frequency.

TABLE I

TE Mode Indexes	Frequency (GHz)	Ratio of Reflected Power at Resonance to Incident Power (dB)	7.58 f (GHz)	Angular Velocity $\frac{d\theta}{dt} = \frac{2\pi \times 7.58 f}{n}$ (10^9 rad/sec)
12, 1, 1	11.84	$-\infty$ (critical)	89.8	47.1
11, 1, 1	10.95	-10.2 (overcoupled)	83.0	47.4
10, 1, 1	10.05	$-\infty$ (initial)	76.2	47.9
9, 1, 1	9.15	-15.6	69.4	48.4
8, 1, 1	8.25	- 3.8	62.5	49.1
7, 1, 1	7.34	- 2.2	55.7	50.0
6, 1, 1	6.42	- 0.5	48.7	51.0

It was decided to try to prevent oscillation in the higher-order axial modes by making their Q's lower than that of the one having a single axial variation. This was accomplished by placing the E_r coupling hole near the end of the cavity. The E_r field of the higher-order modes increases more rapidly with distance away from the end of the cavity. Therefore the coupling to them is heavier. There is the additional effect that the drift tube is closer to a propagating condition for the higher-order axial modes because they are higher in frequency.

For the actual millimeter wave device, the E_r coupling hole was chosen to be 0.107 inch in diameter and the wall thickness was set at 0.015 inch, which is somewhat thicker than a true scaled value. It was decided to make a transition to half-height WR 15 guide at the coupling hole. To check the effectiveness of the mode control system, it was decided to include an H_z coupler in the experimental device. The H_z coupling slot was chosen to be 0.015 inch wide x 0.148 inch long, with a wall thickness of 0.020 inch. If the mode control system operates properly, one would not expect to observe any output power in the H_z -coupled output guide.

Drawings of the model 2 oscillator are shown in Figures 2-4. The changes which have been made are the following:

- (1) reduce the cathode diameter from 0.100 inch to 0.050 inch;
- (2) reduce the length of the drift tube between accelerator and oscillator cavities from 1.75 inch to 0.25 inch and reduce the drift tube diameter from 0.622 inch to 0.540 inch;
- (3) increase the oscillator cavity length from 0.25 inch to 1.00 inch and decrease the diameter from 0.690 inch to 0.582 inch;
- (4) electrically insulate the beam collector;
- (5) introduction of an output coupler which couples to the desired resonance with E_r coupling and perturbs the mode with H_z at that position to spoil its Q.

B. CONSTRUCTION OF OSCILLATOR MODEL 2

Fabrication of parts and assembly of the second experimental oscillator was completed toward the end of this reporting period. The techniques used were essentially the same as those used for model 1. No particular difficulties were encountered in the construction.

In processing, the tube was baked at a temperature of 380° C. The bakeout temperature limitation was determined by the soft glass used to bond the mica, millimeter-wave, output windows.

C. EXPERIMENTAL RESULTS WITH MODEL 2

Initial experimental measurements have been made on the model 2 oscillator. A slight inconvenience that has been encountered with model 2 is that the accelerator cavity has a resonant frequency of 9.68 GHz instead of the design value of 9.40 GHz. It is probable that this change was caused by the change in drift tube diameter from model 1 to model 2, but some unforeseen dimensional change may also have contributed.

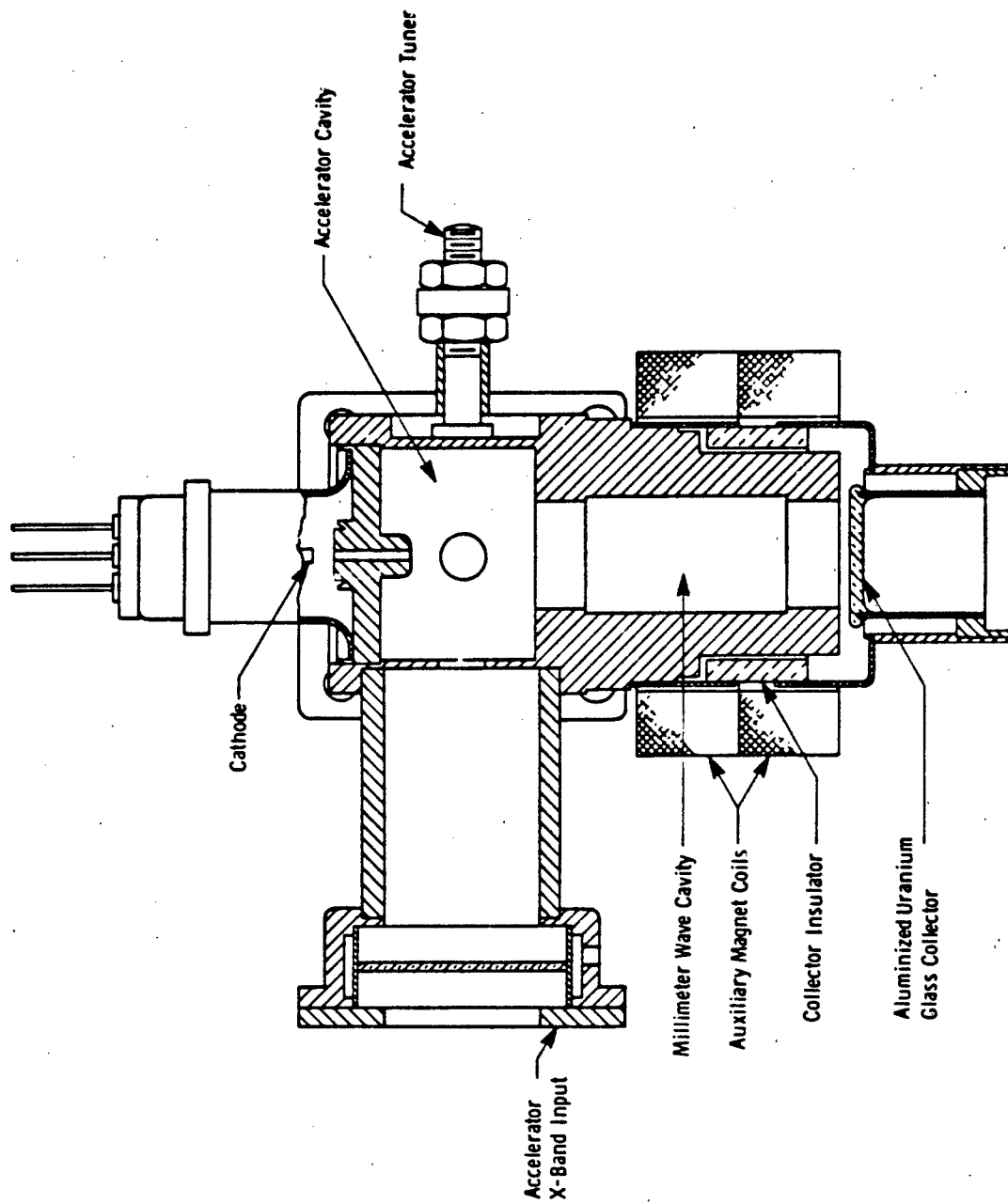


Figure 2. Cross-Section Through X-Band Input Guide for Oscillator Model 2

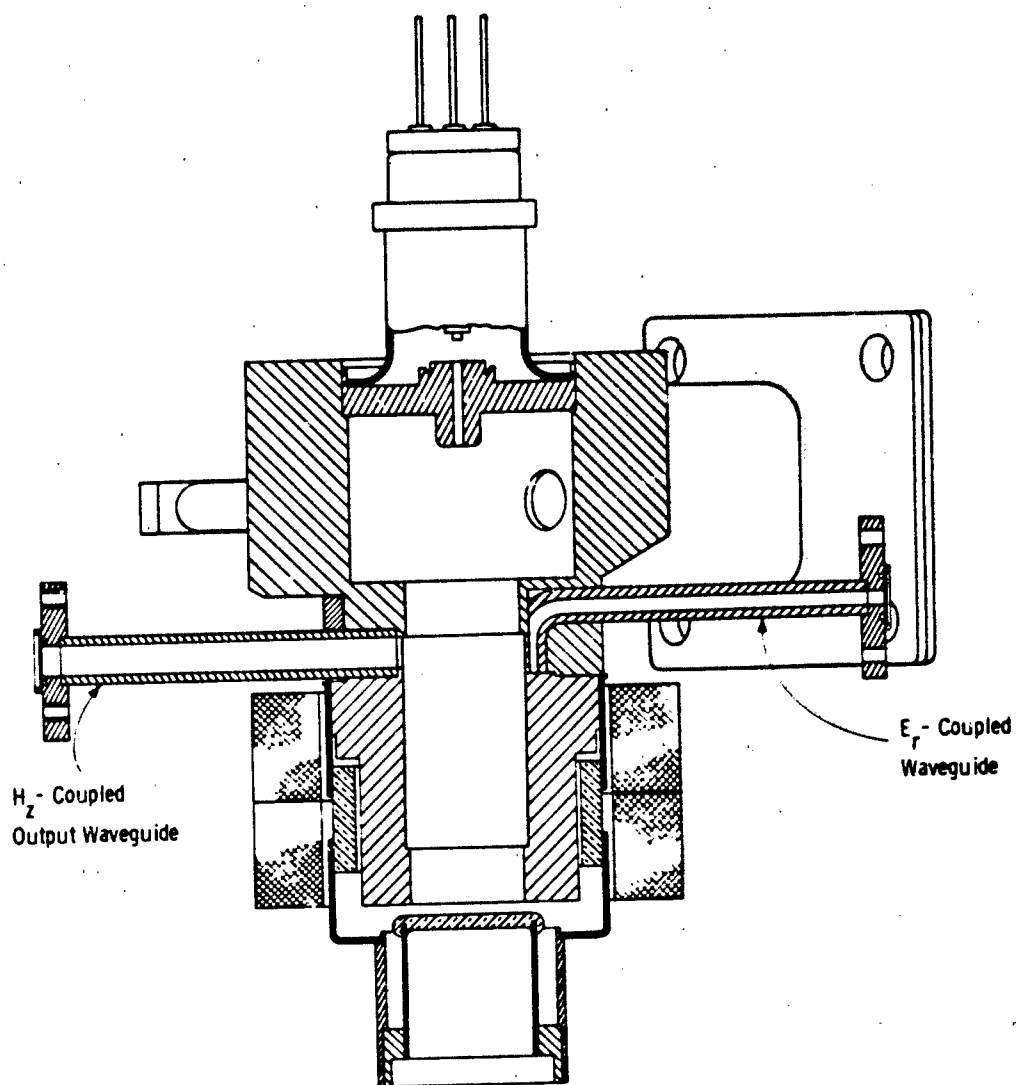


Figure 3. Cross-Section Through Millimeter-Wave Coupling Guides for Oscillator Model 2

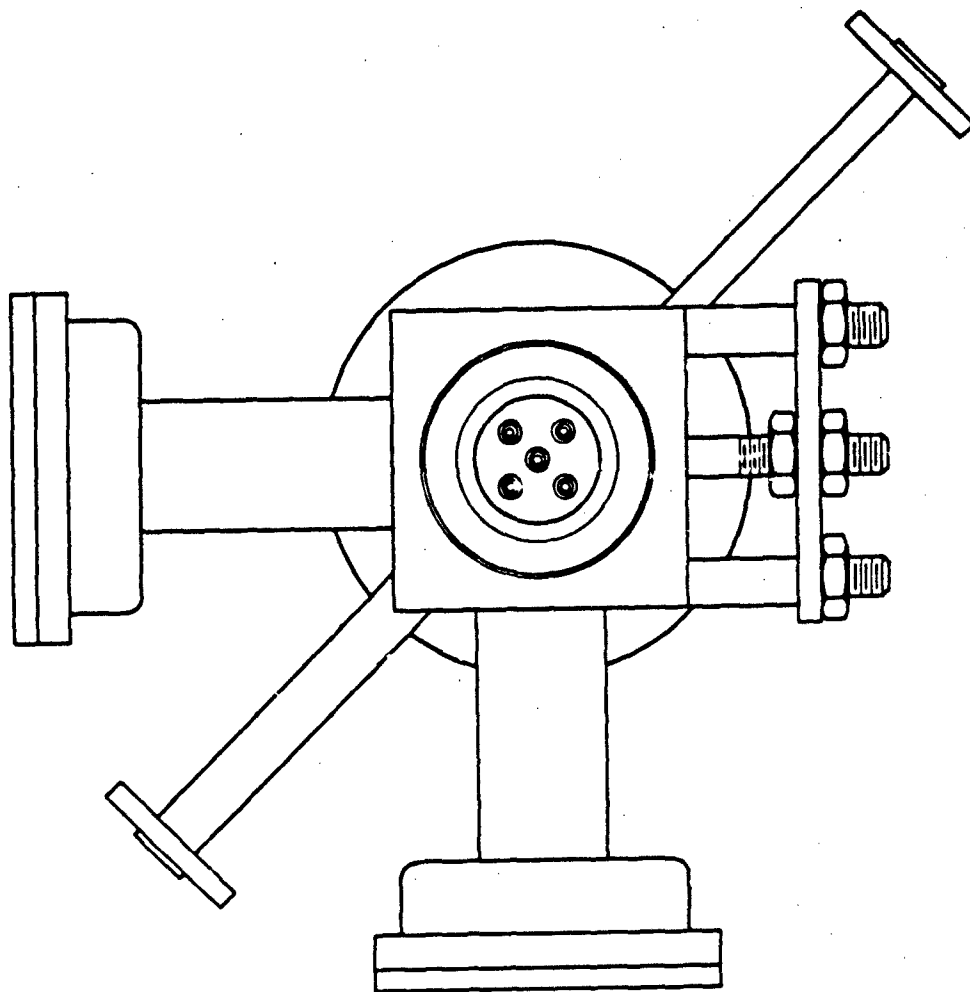


Figure 4. Outline View from Cathode End for Oscillator Model 2

Unfortunately, the 9.68 GHz resonant frequency is just outside the tuning range of the 7008 magnetron that had been used with model 1. This has required changing to a 2J51 magnetron which will tune up to the required frequency, but which has an output power rating of 50 kW maximum.

In the experiments with model 1, an isolator was used between the magnetron and the 3 dB hybrid which divides the power for the two inputs to the accelerator cavity. With an ideal hybrid and ideal cavity tuning, the isolator should not be necessary, since all reflected power should come out the fourth arm of the hybrid into a dummy load. In practice there is some reflection from the hybrid back to the magnetron. With the 2J51 magnetron, operation was tried with the isolator omitted. Pulling effects due to reflected power were observed, but a stable operating point was found by adjusting the line length between magnetron and hybrid. Operation without the isolator is not always stable when high beam currents are introduced into the accelerator, but it is satisfactory most of the time. The avoidance of the isolator insertion loss is advantageous with the lower power magnetron.

Millimeter wave output power has been observed at frequencies of 48.8, 55.8, 62.6 GHz corresponding to $TE_{6,1,1}$ through $TE_{9,1,1}$ resonances in the cavity. Peak powers of 3 - 5 W have been measured coming out of the E_r coupled output guide. Negligible amounts of power are observed at the uranium glass window. Power out of the H_z -coupled guide has not yet been measured. No attempts have been made to optimize the output power. Since the output power starts at a particular value of beam current and occurs at the appropriate frequencies, it is concluded that the desired oscillations are being observed.

The insulated collector screen on model 2 has allowed the observation of the current which is transmitted through the millimeter-wave resonator. Several interesting effects have been observed. When the auxiliary magnetic field is connected as a bucking field, the electron axial velocity through the millimeter-wave cavity is high, and no millimeter-wave output is observed. Under these conditions the beam makes

a fairly well-defined ring on the collector screen, but the screen current is about half of that injected into the accelerator. The reason for the loss of half the current is not understood. It may be caused by some undetected rf oscillation, or it may be caused by some peculiarity in the accelerator.

When the auxiliary magnetic field is used to reduce the electron axial velocity, and the millimeter-wave resonance occurs, the beam pattern observed on the screen is generally quite diffuse, and there is an additional decrease in the beam current reaching the screen. This decrease is reasonably accounted for by the millimeter-wave interaction. The loss of current with no millimeter-wave output needs further investigation.

III CONCLUSIONS

The cold test work on methods of coupling the oscillator cavity to the output waveguide has led to what appears to be a reasonable solution to the problem of properly orienting the cavity resonance. The solution is based on using a large hole to couple E_r in the cavity to the E field in the waveguide. The same hole acts as a perturber for the orthogonal cavity resonance which has H_z at the hole position. The effect of the perturbation is to scatter the energy of the H_z resonance into other cavity modes and thereby lower the Q of the H_z resonance.

The redesign, construction, and assembly of the improved oscillator (model 2) has progressed essentially on schedule. Initial experimental results have been encouraging with the observation of millimeter-wave cavity oscillations at frequencies ranging from 48.8 GHz to 69.5 GHz, corresponding to resonances from $TE_{6,1,1}$ to $TE_{9,1,1}$.

The insulated collector screen has allowed the measurement of the current which actually passes through the millimeter-wave cavity. It has been observed that with no millimeter-wave oscillation present only about half the cathode current is transmitted to the collector when the accelerator power is applied. When the millimeter-wave oscillation is present, about 20% of the cathode current reaches the collector. The loss of current with millimeter-wave oscillation is reasonable, but the loss of current with no oscillation needs further investigation.

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